4.6 Trade Studies

Trade Studies is the System Engineering (SE) element used by multidisciplinary teams to identify the most balanced technical solutions among a set of proposed viable solutions. It is a key tool in developing designs that meet stakeholder requirements in the most cost-efficient manner possible. The application of Trade Studies prevents program/project management from committing too early to a design that may not be cost-effective or meets all system requirements. Through Trade Studies, desirable and practical alternatives that better combine cost and effectiveness may be identified, resulting in beneficial selections among the alternatives. Figure 4.6-1 depicts the Trade Studies Process-Based Management chart.

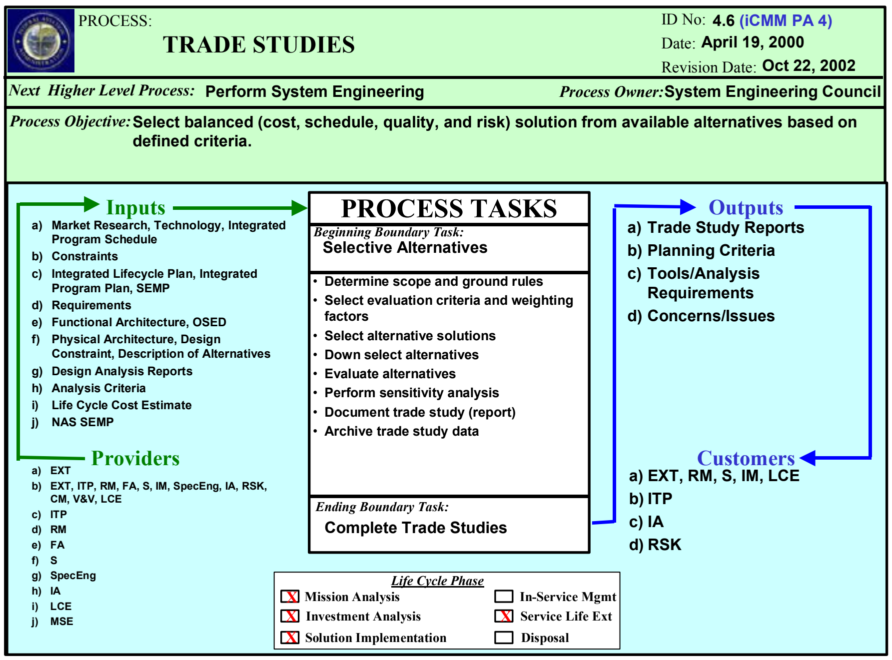

Figure 4.6-1. Trade Studies Process-Based Management Chart

Conducting Trade Studies involves evaluating two or more alternatives to select a preferred option. The Trade Studies process balances such considerations as cost, reliability, testability, supportability, survivability, compatibility, and producibility during each phase of the product development cycle.

A disciplined Trade Studies process is required to fairly evaluate alternative concepts and designs. The process requires that any affected discipline participate in the program/project to the extent needed to arrive at the best-balanced requirements solution. Typically, a Trade Studies leader, who is not a stakeholder in any of the proposed solutions, helps to focus and coordinate the flow of information that occurs during the Trade Studies process.

Trade Studies may be formal and informal, with different emphases, depending on when in the program lifecycle they are conducted. It is appropriate to develop a Trade Studies plan (Integrated Technical Planning (Section 4.2)) for each major problem or issue for which alternatives are being considered.

This section describes the Trade Studies process as a formal decisionmaking methodology used to select among alternative concepts, designs, products, or approaches that satisfy the system implementation and to resolve any conflicts that arise during the system's lifecycle.

4.6.1 Introduction to Trade Studies

Trade Studies are conducted within and across disciplines to support decisions at any phase of the program's lifecycle. The process quantifies and/or qualifies the consequences of selecting various system alternatives in terms of metrics that are traceable to customer requirements and are declared by project management to be project objectives. They support the allocation of performance requirements and the determination of design constraints and are used in evaluating alternative functional architectures obtained from Functional Analysis (Section 4.4). In general, the results of the Trade Studies process may be quantitative or qualitative in nature.

Trade Studies may be performed at any step in the system's lifecycle, but the process begins at the Mission Analysis (MA) phase and continues through first article production. For example, the major goal of the Investment Analysis (IA) phase is to define a set of system requirements that meet the goals and objectives of a mission or a system at an affordable cost and with an acceptable level of risk. During this phase, Trade Studies may be used to select among competing sets of requirements that define alternative system concepts. In a similar manner, the Trade Studies process is used to assist SE.

The following list summarizes the use and emphasis of Trade Studies in the program's lifecycle:

MA phase:

- Define mission requirements
- Resolve conflicting high-level customer requirements
- Evaluate alternative high-level requirements to meet mission needs

IA phase:

- Compare technologies and approaches
- Evaluate concepts to meet high-level requirements
- Select alternative system configurations for further study
- Select concept for preliminary design development and conceptual layouts
- Support Functional Analysis (Section 4.4) and allocation of performance requirements (alternative architectures)
- Establish system configuration
- Support decision for new product development versus nondevelopment products
- Establish system, subsystem, and component configurations
- Select testing methods
- Determine installation locations; check for fit and compatible environment
- Detail design
- Define a best-value design solution that satisfies all system requirements

- Support detailed design analysis
- Compare manufacturing processes
- Determine best order of assembly

Solution Implementation (SI) phase:

- First article, full-scale development
- Resolve unexpected manufacturing issues, such as changing the order of assembly or revising a manufacturing process
- Select alternative designs, solutions (operations, maintenance, integrated logistic), procedures, and configurations

4.6.1.1 Trade Studies Objectives

Trade Studies are conducted at the program's different lifecycle stages to discover the best-value solution, best value to the government, and best value to a set of requirements from technical, cost, or schedules points of view. Trade Studies, also referred to as tradeoff studies or selection studies, are performed for a variety of purposes, including to:

- Choose among alternative design and implementation strategies and solutions based on architecture, performance, and cost in order to meet stakeholder requirements
- Recommend commercial-off-the-shelf (COTS) products for acquisition
- Perform make versus buy analyses, or buy versus lease analyses (Office of Management and Budget (OMB) Circular a.76, Outsourcing Decision)
- Recommend a supplier for services
- Document and justify the selection of a solution for a system requirement
- Reduce risk

Trade Studies provide an objective determination of comparative metrics for various system options. An essential aspect of the analyses performed for these studies is that consistent, configuration-controlled parameters be used in the computations to ensure comparison of likely system solutions.

4.6.1.2 Participants

All elements of the project organization are responsible for Trade Studies. The process requires the participation of various interdisciplinary skills in an integrated manner with the objective of producing an optimum system design.

Design, manufacturing, test, operations, and product support perform lower-level Trade Studies that involve subsystems, components, subcomponents, and software. In the event of utilization of system-level resources contention, program/project management coordinates with the stakeholder organizations to resolve issues and establish priorities. It is recommended that Trade Studies affecting hardware and software account for system issues related to software, operations, procedures, training, and other nonmaterial-related solutions.

To determine impacts across interfaces, it is recommended that SE integrate the Trade Studies performed by various groups.

4.6.2 Inputs to Trade Studies

Inputs to the Trade Studies process may be divided into two categories: stakeholders and project. The stakeholder inputs include the operations concept, program requirements, and system requirements. The project inputs include design analysis report (DAR), Functional Architecture (Section 4.4), DAR (Section 4.8), results from Validation and Verification (Section 4.12), and Lifecycle Cost Estimates from Lifecycle Engineering (Section 4.13).

The Trade Studies process presupposes that alternatives have been identified that are evaluated as specified by the process objective. To complete this task:

- Requirements, Constraints, expectations, assumptions, goals, and regulations shall be clearly understood
- Design options, including Baseline and other criteria, shall be provided or developed
- Relevant plans and documents shall be provided

4.6.3 Trade Studies Process Tasks

The methodology to evaluate system alternatives is described in the following paragraphs. The Trade Studies process consists of the following tasks:

- Determine scope and ground rules
- Define evaluation criteria and weighting factors
- Select alternative solutions (brainstorm possible solutions), if not provided
- Down-select alternatives
- Evaluate alternatives
- Perform sensitivity analysis
- Review results and form conclusions
- Document the Trade Studies

These steps seldom are performed sequentially. Certain steps, such as definition of evaluation criteria, may be repeated several times as alternatives are defined and evaluated. Figure 4.6-2 depicts the overall Trade Studies process.

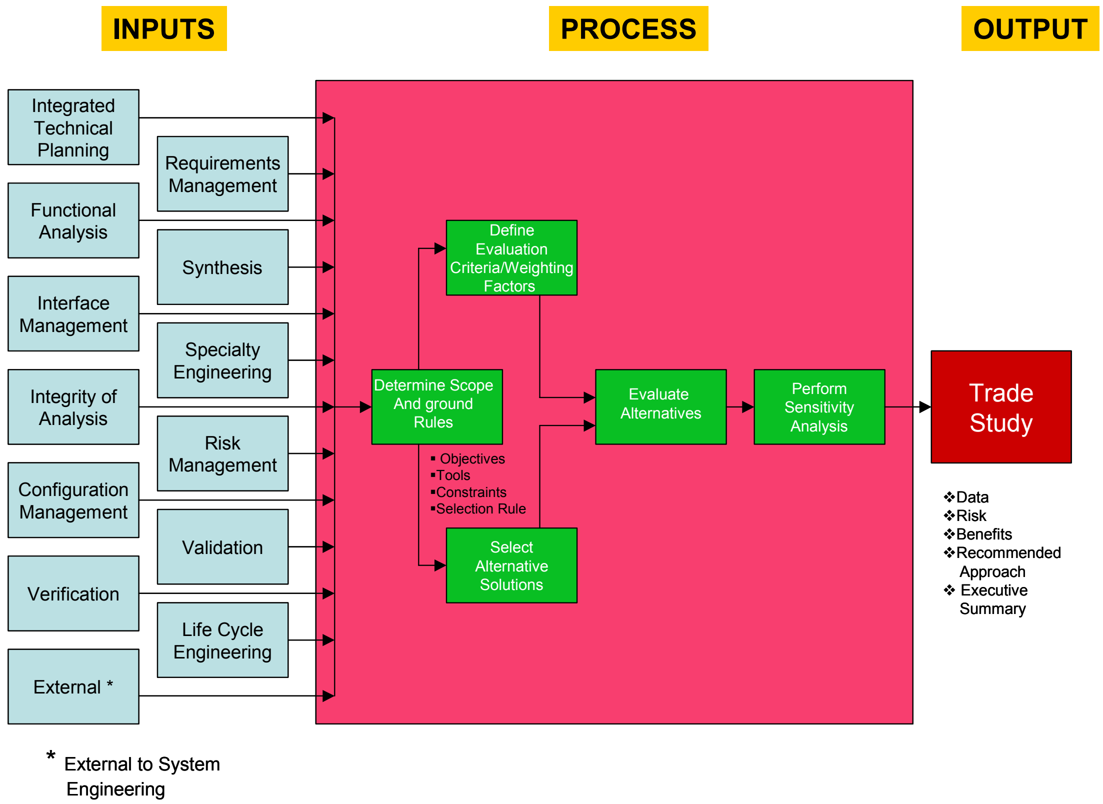

Figure 4.6-2. Trade Study Process

4.6.3.1 Task 1: Determine Scope and Ground Rules

To complete Task 1, perform/consider the following checklist of actions/issues:

- Determine the specific goals of the Trade Studies and the Requirements to be met before establishing the scope and methods of the study:
  - Consider all viewpoints of stakeholders (e.g., users, developers, managers, and operations and maintenance personnel) to accomplish this goal
  - Ensure that input is obtained from all customers associated with the study and that the stakeholders' viewpoints are clearly understood and documented
  - Understand and resolve differences between competing viewpoints and any underlying biases before continuing the evaluation process
- Use the methodology described in Requirements Management (Section 4.3) to define and analyze the Requirements for the Trade Studies:
  - Select Requirements to bound the Trade Studies into four major categories: functional, performance, operational, and programmatic
  - Base the Requirements on the goals established for the study and adjust the level of detail of the Requirements to the scope of the particular study

- Ensure that the Requirements, which are used as a basis for criteria against which alternatives are evaluated, are accurate, unambiguous, verifiable, complete, and appropriate
- Obtain the customer's approval on the goals and Requirements for the tradeoff study

- Define the system's goals and objectives and identify the Constraints to satisfy:
  - Recall that in the early phases of the system's lifecycle, the goals, objectives, and Constraints are usually stated in the operational terms; when the system architecture and design have been determined or established, the goals and objectives are usually stated as performance requirements
- Spend time up front clearly defining the problem and jointly coordinating with the respective internal and external customers the key Requirements that any solution needs to meet. Achieving consensus with affected team leaders regarding the real problem to be resolved saves significant time in the overall process.
- Establish a multidisciplinary team that is able to support the analysis effort from start to finish. Having expertise within each discipline ensures that alternatives are thoroughly evaluated, leading to the most accurate assessment results. Available budget and time control most studies; therefore, when equipped with this information, team members realize how far they may pursue alternatives.
- Develop an attainable schedule as well as identify major Trade Studies milestones. It is recommended that the degree to which excursions from the baseline concept are allowed also be defined. A study lacking clear boundaries easily grows far beyond the available resources.

It is recommended that the Trade Studies team leader coordinate items that influence subsystems and assess the impact on his/her area. It is also recommended that subcontractors, as well as those on the Trade Studies team, consider and identify previously developed hardware and software components, non-developmental items (NDI), and COTS hardware and software as candidates for utilization in the Trade Studies. Additional items for the team to consider and identify are common components in different parts of development to share across development groups or across configuration items.

Before the Trade Studies process is conducted, the decisionmaking body responsible for the affected baseline shall approve the Trade Studies plan.

4.6.3.2 Task 2: Define Evaluation Criteria and Weighting Factors

The definitions of measures and measurement methods for system effectiveness, system performance, and system cost are related to the definition of goals and objectives and Functional Analysis (Section 4.4) performance. These measurements are the decision criteria. Each quantitative measure shall have a defined measurement or computational method. This task initiates the analytical portion of the Trade Studies process, as it involves using quantitative methods.

The definition of evaluation criteria requires considerable engineering judgment and interaction with the stakeholder to establish the appropriate criteria, associated weights, and scoring methods. For example, supporting missions with tight schedules requires heavy weighting of schedule risk, while supporting missions with more flexible schedules generally emphasizes low cost while accepting higher schedule risks. Sufficient comments shall be provided for each evaluation criterion to ensure evaluator and stakeholder comprehension. Stakeholder approval shall be obtained before proceeding to the next task.

The technical requirements that potential solutions need to achieve serve as the criteria against which alternative concepts are measured. The selected criteria may include limits of minimum acceptable values and desirable attributes that permit judging of candidates against each other. Trade Studies leaders are encouraged to use Quality Function Deployment (QFD) to help to define the evaluation criteria and weighting factors applicable to the Trade Studies. These criteria are defined based on the technical requirements that determine if a design is acceptable to the Stakeholder Needs.

Evaluation criteria are more meaningful if they represent measurable characteristics, which is not always possible. It is recommended that criteria on cost and programmatic risk be included. Alternatives may be evaluated based on projected fixed and variable cost using risk factors, when applicable, to derive expected costs. It is also recommended that elements not directly related to cost (e.g., weight, production cycle time) have criteria established to associate cost with changes in the elements. Trade Studies shall address these criteria.

An experienced, multidisciplinary team shall brainstorm a list of additional criteria suitable for the study's intent if all feasible alternatives are to be identified and thoroughly evaluated. Each criterion shall be described to a level of detail such that its intent is clear to all team members. This detail ensures that all participants are well aware of specified and derived Requirements affecting evaluation.

When a particular study is planned, the effort and cost of that study shall be balanced against the impact (e.g., cost, schedule, and technical risks) on the study's scope and methodology. An overly ambitious and costly study among low-impact alternatives is as serious as the failure to adequately evaluate high-impact alternatives. For a simple evaluation of several low-impact alternatives, subjective evaluation and consensus may be sufficient. For complex studies with higher impact, the following is recommended:

- Define evaluation criteria based on the Requirements analysis.
- Determine relative weights for the evaluation criteria based on the Requirements analysis.
- Prepare a scoring matrix that assigns a row for each evaluation criterion and a column for each alternative to be evaluated, with comment fields for each criterion.
- Define a method for assigning a score to each element in the scoring matrix.
- Assign a score for each criterion for each alternative:
    - Select scores in such a manner that the higher the score, the more favorable the evaluation; use an odd number of integers so that the middle score represents an average rating
    - Use small integers, typically 0 to 5, to represent scores; a range of 0 to 2 may be adequate; a range in excess of 0 to 10 is not recommended
    - Determine a method of recording items that is unable to be scored; define the scoring method to be used; recording a blank for unknown information often is useful

- Prepare a weighted score matrix that assigns a row for each evaluation criterion and its weight and assigns a column for each alternative to be evaluated. The weighted score recorded for each element in the matrix is the product of the weight for that criterion and the corresponding score in the scoring matrix.

Figure 4.6-3 is a sample decision analysis matrix.

Decision Factors / **Alternatives**	Decision Factor 1		Decision Factor 2		...	Decision Factor n		Total Weighted Score
	Weight = 1		Weight = 1.5		...	Weight = 2.5		
	Score	Weighted Score	Score	Weighted Score	...	Score	Weighted Score	
Alternative 1	7	21	4	6	...	8	20	47
Alternative 2	8	24	10	15	...	10	25	64
⋮	⋮	⋮	⋮	⋮	...	⋮	⋮	⋮
Alternative n	10	30	5	7.5	...	12	30	67.5
Alternative n+1	⋮	⋮	⋮	⋮	...	⋮	⋮	⋮

Figure 4.6-3. Decision Analysis Matrix

Stakeholder approval of the proposed evaluation method shall be obtained.

Stakeholders and internal technical experts are used to establish meaningful evaluation criteria. Criteria for which all potential alternatives are equal in value are not used in the evaluation because they do not add value to the process.

Defining evaluation criteria often requires several iterations before the final criteria are determined. Evaluation criteria are defined based on the analysis of Requirements. Bias shall be avoided when evaluation criteria are established (e.g., acceptance of an existing system or product as the de facto standard for evaluation). The following evaluation criteria are applicable to a wide range of Trade Studies:

- Development cost
- Lifecycle cost
- Requirements compliance
  - Functional
  - Performance
  - Operational
  - Programmatic
- Technical risk (Maturity)

    1. Reliability, Maintainability, Availability (RMA)
    2. System Safety
    3. Quality
    4. Human Factors
    5. Electromagnetic Environmental Effects (E3)
    6. Hazardous Materials
- Budget risk
- Schedule risk
- Operational complexity
- Vendor assessment
- System maturity
- Development support tools
- Test support tools
- Development team familiarity with candidate hardware and software
- Quality of logistics support

Evaluation criteria that apply specifically to the Trade Studies shall be selected, adding additional relevant criteria, such as security, as needed. For each evaluation criterion, established threshold values that may be used to evaluate the alternatives on a pass/fail basis shall be identified. An example criterion is: “The system MTBF shall be 10,000 hours or greater." For the remaining criteria, a weight and scoring range shall be assigned for use with the weighted matrix evaluation method.

Criteria are ranked and grouped into three categories so that the assigned weights reflect their criticality. The most critical criteria are assigned large weights and flagged so that any alternative with low scores for these criteria influence any subsequent analysis. Mid-critical and noncritical criteria are assigned smaller weights; it is recommended that noncritical criteria have a negligible effect in further analysis.

4.6.3.3 Task 3: Select Alternative Solutions

Once the evaluation method is established, all available resources are used to develop viable alternatives and solutions. Trade publications, prospective bidders for service contracts, technical staff, stakeholders, and managers, as appropriate, are helpful resources in developing a set of alternatives that may potentially achieve the goals and objectives of the system (e.g., architectures, designs, COTS products).

Based on defined ground rules, the alternative development phase is intended to evaluate multiple alternatives and narrow the prospects for extensive evaluation. The importance of creativity is especially emphasized, as this task may or may not affect the alternative design solutions previously submitted.

The evaluation criteria and detailed Requirements shall be used to synthesize alternative solutions. In defining alternative approaches, developing the alternatives often requires lower-level Trade Studies, which enables a hierarchy of design alternatives. A trade tree that reflects the complete hierarchy of trades to address when performing the top-level Trade Studies shall be drawn. The trade tree shall contain a number of high-level system architectures, which prevents focusing on a single architecture. To eliminate undesirable alternatives, for each trade item in the trade tree, the tasks in the sections above shall be repeated until a complete trade tree is generated, and the objectives, Requirements, evaluation method, and evaluation criteria are defined. Top-level objectives and Requirements are allocated to successively lower levels of Trade Studies in the trade tree. The allocated objectives and Requirements are used to define the evaluation methodology and criteria, and evaluation is performed, as described in the following paragraphs.

Each design alternative shall be thoroughly assessed. Potential design approaches for each Requirement shall be reviewed against potential approaches for other Requirements in order to identify possible interactions. It is recommended that interactions that might affect the cost of, or make one solution feasible, be documented and handled as linked decisions throughout the Trade Studies process.

Often, risk is the deciding factor in candidate selection. A complete technical analysis identifies and quantifies technical risks and develops contingency alternatives. Therefore, the technical and schedule risks associated with each candidate system are identified, and the probable gain and loss for each risk are analyzed. Also, an acceptable level of risk for a given gain is defined, and efforts are undertaken to minimize new, unproven, complex, or unusual Requirements for hardware, software, and firmware. The use of untried elements is minimized by recommending proven substitutes whenever possible.

A technical analysis of schedule risk areas is performed, and all long-leadtime items, which are the schedule drivers, are identified. How the design affects the development schedule is discovered, and all system elements and resources that may be available when needed are determined. All single-source items that may be potential risks are identified, and a recommended level of schedule contingency, as appropriate, is defined.

Expected operational scenarios for each candidate system to assess the interactions of the design alternatives are defined. Also, the expected system growth over the planned system life is determined to assess system design flexibility and expandability. Because system sizing is based on the anticipated workload, every effort to ensure an accurate workload forecast is made, as improperly sized systems result in unnecessary cost and/or insufficient capacity. Human workload and scenario definitions are used as drivers to assess performance, utilization, and capacity of the system under anticipated operational conditions. (Specialty Engineering (Section 4.8) provides guidance on this topic.)

Once a set of possible alternatives has been selected, the next task is to collect data on each to support the evaluation of the measures by the selected method. The data collection, directed by the Trade Studies leader, emphasizes the role of the disciplines, such as reliability, maintainability, integrated logistics, producibility, software, testing, operations, and costing. Figure 4.6-4 is an example of a Trade Studies table.

Criteria	Alternative 1	Alternative 2	- - -	Alternative N
Cost ▪Initial ▪Recurring	High low	Medium Low	- - -	Low Low
Performance	Low	High	- - -	New Design
Reliability Maintainability Availability	Medium	High	- - -	Medium
Risk ▪Cost ▪Technical	Low (20%) Low (25%)	Low (10%) Low (20%)	- - -	Low (10%) Medium (35%)

Figure 4.6-4. Example Trade Study Table

4.6.3.4 Task 4: Down-Select Alternatives

When numerous possible alternatives are identified, a detailed analysis of each one may not be cost-effective; therefore, down-selection of candidates is recommended. Identifying high-risk candidates and candidates with questionable feasibility or high lifecycle cost helps to reduce the number of alternatives to be studied. Screening the alternatives against the selection criteria eliminates these candidates. If one of a closely grouped set of alternatives is down-selected, it is recommended that all alternatives in that group be down-selected. Any relationship that is not the same for each down-selected alternative and the baseline becomes part of the detailed Trade Studies. Each alternative is defined to an appropriate level of detail to differentiate the alternative with respect to the technical requirements, which typically include layouts, tooling concepts, cost studies, and other detailed analysis. When only the down-select Requirements are the focus, the effort is simplified to only those Requirements that are different among the design alternatives and the baseline.

The down-selected alternatives are provided to all disciplines involved to ensure that each has the opportunity to evaluate the impacts. This process provides discrete impacts for each area used to select the preferred alternative. It is recommended that this process be performed in parallel with each discipline preparing its inputs simultaneously.

4.6.3.5 Task 5: Evaluate Alternatives

The next task in the Trade Studies process is to quantify the outcome variables by computing estimates of system effectiveness, underlying system performance or technical attributes, and system cost. If the needed data has been collected and the measurement methods (e.g., models) are in place, this step, in theory, is mechanical. In practice, considerable skill often is needed to obtain meaningful results.

Recommended Task 4 actions include the following:

- Perform a detailed evaluation of all approved viable alternatives. An individual or a small group may perform this evaluation. Record any problems or questions. If a weighted matrix method is used, finish scoring without reference to weights or flags.

- Evaluate the alternative approaches relative to the evaluation criteria when performing the Trade Studies process.
- Identify any alternatives with high-weighted scores that narrowly failed the pass/fail criteria. Discuss these alternatives with the stakeholder.
- Evaluate cost factors separately from the remaining evaluation criteria throughout the process. In some cases, none of the alternatives may satisfy all pass/fail criteria. In such cases, relax one or more pass/fail criteria, investigate additional alternatives, or report to the stakeholder that no entirely acceptable alternative has been found.

Ideally, all input values are precisely known, and models perfectly predict outcome variables. Since this case is not typical, it is recommended that the Trade Studies leader supplement point estimates of the outcome variables for each alternative with computed or estimated uncertainty ranges. For each uncertain key input, it is recommended that a range of values be estimated. Using this range of input values, the sensitivity of the outcome variables may be gauged, and their uncertainty ranges calculated. Figure 4.6-4 is an example of a Trade Studies table.

The baseline reference method, relative rank method, and cost assessment method are several methods used to evaluate alternatives and are discussed in the following paragraphs.

4.6.3.5.1 Baseline Reference Method

The baseline reference method requires a baseline or legacy design and a set of associated databases on the use of that design. Alternatives are evaluated against the baseline design or other reference using the selected evaluation criteria. If an alternative is clearly better than the baseline, it is marked as a plus (+); clearly worse than the baseline (-); same as baseline (S); and unacceptable as the baseline (U). This evaluation requires a team effort of all disciplines participating in the study, with team agreement for each rating. It is recommended that notes be maintained as to why ratings are given for each relationship. Using numbers or ++/-- may expand the sensitivity of the +/- system. However, doing so slows the evaluation process and places dangerous emphasis on the matrix as a tool that delivers answers more definitive than the process warrants. When making the +/- decision, the magnitude of the difference shall be considered; however, the process of marking an only marginally better feature as + compared to the baseline shall be avoided.

Generally, alternatives with a U relationship are eliminated, or the U condition is removed; however, there are exceptions to this rule. An exception may be when the Trade Studies process is conducted to determine whether there are sufficient benefits from an alternative to justify a request for a specification change. Also, an alternative in a study may present itself that significantly improves the overall system performance but requires a specification change. It is recommended that common sense be used when U relationships are evaluated and that the users' needs be considered.

Once relationships are defined for each alternative and technical requirement, the overall value of merit of the alternative is calculated. A value of +1 is assigned to each (+) rating, and a -1 to each (-) rating. A relative weight may also be assigned to each evaluation criterion if not all criteria are considered equal. QFD may help to determine this importance weighting.

It is recommended that the following actions be taken when the baseline reference method is used:

- Multiply the importance weighting and the evaluation and then perform the sum calculation for each alternative. No calculation is performed for the same evaluations because this method of evaluation is relative to the baseline. The overall importance rating is a figure of merit for each alternative. The higher the importance rating, the better the alternative for the given design requirement. However, this guide is only relative. Do not differentiate alternatives by closely grouped importance ratings. If, for example, three concepts fall in a range of 10-20 and the other is -30, the alternatives in the group 10-20 are basically equivalent.

- Review each alternative to gain an overall understanding of the meaning of the final importance rating. It is recommended that the team review all the alternatives with negative relationships and develop supplemental alternatives that eliminate these negatives, resulting in additional viable alternatives. Some of these alternatives use portions of the previously developed alternatives. The development and evaluation of subsequent alternatives shall follow the procedures used for initial alternative development. When supplemental alternatives are developed, low sensitivity of the +/- system is avoided. Developing supplemental alternatives is critical to a successful Trade Studies. A "zero change" option normally is included for comparison.

4.6.3.5.2 Relative Rank Method

The relative rank method uses the Kepner and Tregoe technique to evaluate alternatives. This technique evaluates each alternative against the selected criteria and establishes a ranking for each criterion. Weighting of the criteria is defined by category, while the trade options are graded in their appropriate columns according to the scaling factors over the range 0 to 4. The average ranking within each category is multiplied by the criteria weighting to determine a score. Scores are summed across the criteria for a total.

4.6.3.5.3 Cost Assessment Method

The cost assessment method is similar to the baseline reference method, with the exception that the alternatives are reduced to rough order of magnitude (ROM) estimates of fixed and variable costs. Elements that do not reduce directly to cost (e.g., weight, production cycle time) are translated to cost using common criteria described in "Task 2: Define Evaluation Criteria and Weighting Factors" (Paragraph 4.6.3.2). If risks are present, risk projections are used to calculate an expected value.

As cost is a major factor in selecting among candidate systems during system design, development, implementation, and operational costs shall be considered when the lifecycle costs of candidate system configurations are evaluated. A refinement of earlier ROM cost estimates is required to complete the information needed to select the system configuration. It is recommended that the estimate include estimates submitted by major subcontractors and vendors and contain sufficient cost detail to answer client questions.

In addition, it is recommended that the following actions be taken when the cost assessment method is used:

- Determine the relative complexity and risk of each candidate system configuration.

- Identify how each candidate system configuration proposes to handle stringent system requirements, such as response time, transaction processing time, and throughput.

- Analyze how each candidate configuration meets special system requirements for a high level of reliability and availability or for quick recovery or automatic failover.
- Highlight key factors that result in lower cost and risk. Discuss the factors with the stakeholder, including the option of analyzing a more simple system that addresses only the most critical requirements set. This type of analysis gives the stakeholder a minimum system cost benchmark to assess cost of the candidate system and functionality of each requirement.
- Include the tradeoffs among hardware, software, and manual operations as part of the cost analysis, and identify the most sensitive cost drivers of each candidate system. If the system has security requirements, also consider security cost drivers.

4.6.3.6 Task 6: Perform Sensitivity Analysis

Sensitivity analysis is used when the solutions are nearly equivalent in scoring and, in some cases, may be required even if the scoring is equivalent.

Recommended Task 5 actions include the following:

- If using a weighted matrix evaluation method, analyze all alternatives to determine if the differences between the scores are truly significant and if minor variations in the raw scores and weights might affect the selection. Reference any questions or problems noted by evaluators. For each compliant alternative, including any solution that is compliant based on redefined pass/fail criteria, determine if any weighted score or total for a group of related weighted scores is sensitive to variation of weights or scores.
- Evaluate the effect on weighted scores of varying weights. If some weights are determined by compromise, the range of reasonable values discussed during the definition of evaluation criteria (Paragraph 4.6.3.2) provides useful guidance for such variation.
- Evaluate the sensitivity of weighted scores to variation of scores. If a number of evaluators have evaluated the alternatives against a given criterion, the range of scores recorded provides useful guidance for such variation.
- Record the ranges of scores and weights evaluated for each criterion. Compute the upper and lower bound for weighted scores (and groups of weighted scores). Document the data in a matrix corresponding to the score and weighted score matrices.
- By inspection or use of a suitable statistical test, determine if any of the variations are large enough to require special attention (i.e., more detailed investigation to ensure the accuracy of the evaluation).
- Evaluate the effect on weighted score totals, including or excluding criteria flagged as noncritical.

Typical outcomes of the sensitivity analysis and review of results include the following:

- **Case 1:** One alternative emerges as the optimal choice if it meets all critical requirements, has the highest weighted score (with a range that does not overlap the range of another alternative), and has the lowest cost.
- **Case 2:** A cluster of alternatives is acceptable (i.e., each alternative in the cluster satisfies all critical requirements, its weighted scores have overlapping ranges, and its cost is competitive).

- **Case 3:** No single, entirely satisfactory alternative is found.

Case 1 is the most straightforward for the stakeholder. Case 2 may be resolved by reviewing evaluation results with the stakeholders. If a weighted matrix evaluation method is used, inspecting the score and weighted score matrices may reveal patterns that are helpful and clear in the decisionmaking process. A review of weights and criteria may indicate that weights may be modified, which may resolve the overlap. Additional factors may be identified as criteria to resolve the overlap. If the overlap of weighted scores persists, the lowest-cost alternative may be selected. Case 3 is the most difficult to resolve. A review of evaluation criteria, especially pass/fail and critical criteria, may indicate that no satisfactory alternative has been identified by the study. In this case, engineering judgment and discussions with the stakeholder shall be used to define additional alternatives or to accept a less than optimal alternative.

Figure 4.6-5 depicts typical utility curves used for sensitivity analysis.

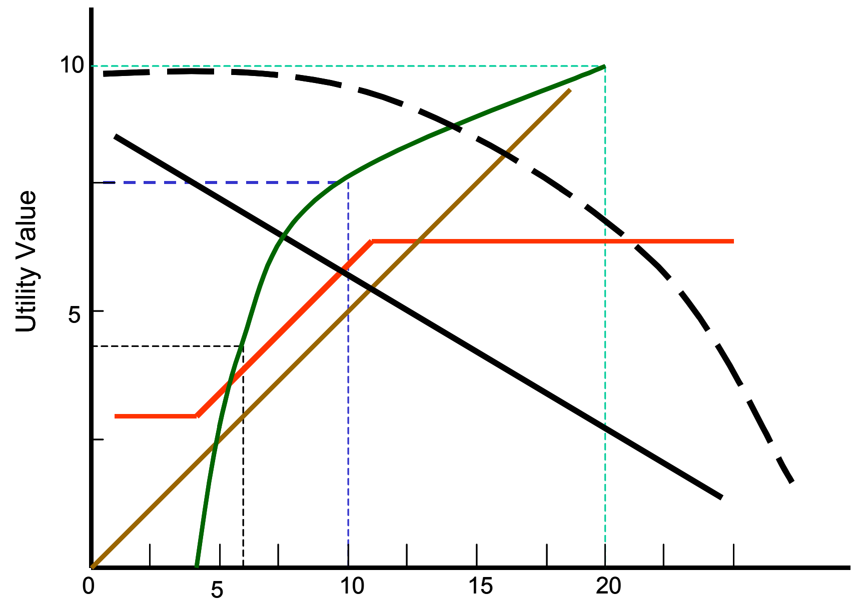

Figure 4.6-5. Example Utility Curves

4.6.3.7 Task 7: Review Result and Form Conclusions

This part of the Trade Studies process typically presents one alternative that balances the Requirements and a "zero change" option for comparison. While the defined decision authority makes the final decision, a recommendation by the Trade Studies team is essential. All results shall be reviewed, any necessary additional data obtained, and evaluations and preliminary conclusions revised as needed. Any or all parts of the study may be repeated.

If the evaluation's intent is to select a product or service, it may be useful to review preliminary conclusions with vendors to ensure that no misunderstandings have occurred. Delaying such reviews until this phase of the evaluation avoids much of the risk of biasing the overall process.

When the evaluation is completed and deemed reliable, cost estimates for each alternative shall be prepared. Weighted scores for evaluation criteria are related to benefits associated with the evaluated alternative. The cost of an alternative divided by the total score for that alternative is a measure of the cost/benefits of that alternative.

At this point, the alternatives are now ordered based on the technical requirements and quantified impacts. It is recommended that changes from the baseline design technical performance and the decision criteria used during this evaluation be highlighted.

4.6.4 Outputs of Trade Studies

The outputs of the Trade Studies process are a report with an executive summary and a design/manufacturing decision document.

4.6.4.1 Trade Study Report

A Trade Study Report is prepared for each study. The report documents the study results and provides traceability to decisions made during the program's lifecycle. The report provides the traceability needed to substantiate design and configuration changes to the baseline design and also documents the decisionmaking process that selected one alternative over another. Additionally, it describes the effects of selecting a particular alternative among trades and clearly notes affected areas that were included in the Trade Studies assumptions, as well as affected areas that were not included in the associated trade. Once the report is completed, the Trade Studies leader is expected to coordinate the report with all affected team leaders before submitting it for approval and signature.

The Trade Study Report is prepared using a format appropriate for documenting and communicating the results, conclusions, risks, benefits, and recommendations to the decisionmaker. It is recommended that the format be standardized wherever possible to satisfy individual program needs. At a minimum, it is recommended that the following be included, but not limited to:

- Clear problem statement
- Identification of affected Requirements
- Ground rules and assumptions
- Decision criteria
- Resource requirements statement to accomplish the study
- Schedule to accomplish (proposed and actual)
- Evaluation of all potential solutions and screening matrix
- Comprehensive array of feasible alternatives
- Comparisons of alternatives using decision criteria
- Technical recommendation of the Trade Studies team
- Documentation of any decisions leading to the final technical recommendation

The following is a suggested report format. Each project may enhance the standard outline as needed by adding subsections and separately numbered items to the sections. Each project may also add sections and subsections for special topics and delete sections and subsections that are not applicable.

Table of Contents

1 Introduction
- 1.1 Scope
- 1.2 Applicable Documents
- 1.3 Definitions

2 Study Summary

3 Requirements Summary

4 Evaluation Criteria
- 4.1 Evaluation Criteria and Scoring Method
- 4.2 Evaluation Criteria and Changes During Study

5 Alternative Solutions

6 Results
- 6.1 Evaluation Approach, Scores, and Analysis
- 6.2 Conclusions

Appendices

List of Acronyms

References

4.6.4.2 Design/Manufacture

Once the Trade Study Report is approved, the design decision/manufacturing document is produced, outlining the impacts and actions necessary to implement the alternative recommended in the Trade Studies into the baseline configuration. In general, this document describes the rationale required to substantiate the change. The report then becomes an attachment to the design decision/manufacturing document and serves as the technical basis for the option to be implemented. The design decision document is submitted to the appropriate control authority to authorize implementation into the baseline configuration. The control authority is also required to maintain the report and the design/manufacturing decision document for the program's lifecycle.

4.6.5 Trade Studies Tools

4.6.5.1 Quality Function Deployment

QFD is a methodology used to ensure that the stakeholders' operational needs and requirements are gathered, interpreted, and deployed in developing a product or service. The primary objective of QFD is to eliminate three major problems: difficulty in gathering and interpreting stakeholder's requirements; loss of information; and different individuals and functions using varying interpretations of the same requirements. QFD provides a Trade Studies tool that screens alternatives using weighted selection criteria. QFD is recommended for use whenever:

- Stakeholder requirements are vague, ambiguous, or self-contradictory
- Multiple disciplines are involved in the collection and interpretation of the requirements
- Multiple solutions are feasible with no clear choice
- Lack of an obvious feasible solution
- Cost and/or risk appear to be unacceptably high

QFD (see http://www.shef.acu.uk/~ibberson/qfd.html) requires teamwork among the multiple disciplines that make up a program/project team to address requirements from multiple perspectives. It is recommended that QFD involve the customer, representatives from the product development and support functions, and suppliers. It is also recommended that a team attempting to conduct a QFD exercise for the first time receive training before the start of the QFD exercise and support from an experienced product-oriented QFD expert.

4.6.5.2 Modeling and Simulation

Models and simulations are standard engineering tools that represent the key features of a system and the interactions of those features with each other and the outside environment. The defining feature of any model is its purpose. In general, a model represents how the system operates in its environment. An excellent guideline to follow is to select the least complex model that provides the most visibility into the problem.

4.6.6 Trade Studies Process Metrics

Quality may be measured by the degree to which the project objectives are satisfied, as noted in “Trade Studies Objectives” (Paragraph 4.6.1.1); objectives are satisfied when they may be numerically quantified (e.g., increase of payload capability). For imprecise objectives, project management may decide on a different type of assessment (e.g., yellow/red/green).

Timeliness may be measured by compliance with the schedule. It may be measured by when the decision support provided by the studies is available for the decision to be made.

Resources consumed to reach the required decision support level may identify efficiency, which may include labor hours, computer usage, and schedule time.

Cycle time may measure the duration from the creation of system alternatives to the delivery of the decision support products discussed in “Outputs of Trade Studies” (Paragraph 4.6.4).

Process performance is measured and recorded on a regular basis. Process users (teams or equivalent functions) accumulate the following metrics, at minimum, to evaluate the performance of this process:

- Percentage of studies performed in which none of the alternatives emerged conclusively as the best solution, thereby driving a decision based on other factors
- Percentage of studies in which the recommended alternative was not subsequently selected
- Percentage of planned discipline viewpoints, as defined by the study scope, that actively participated in conducting the Trade Studies

The decisionmaker completes satisfaction assessment.

4.6.7 References

1. Blanchard, B. "System Engineering Management." 2nd Ed. New York: John Wiley & Sons, Inc., N.Y.
2. Blanchard, B., and W. Fabrycky. "Systems Engineering and Analysis." 2nd Ed. Englewood Cliffs, New Jersey: Prentice Hall.
3. Defense Systems Management College. "Systems Engineering Fundamentals." Fort Belvoir, Virginia: Defense Systems Management College Press, 1999.
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